The Chemically Homogeneous Binary Channel for the Formation of BH Binary Mergers

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- the detection of BH-BH mergers by aLIGO has started the era of gravitational-wave astronomy
- diversity of BH-BH properties

→ variety of formation channels

I. Dynamical formation

a. in dense clusters: dynamical interactions → close BH+BH binaries

b. in triple systems (see Toonen's talk)

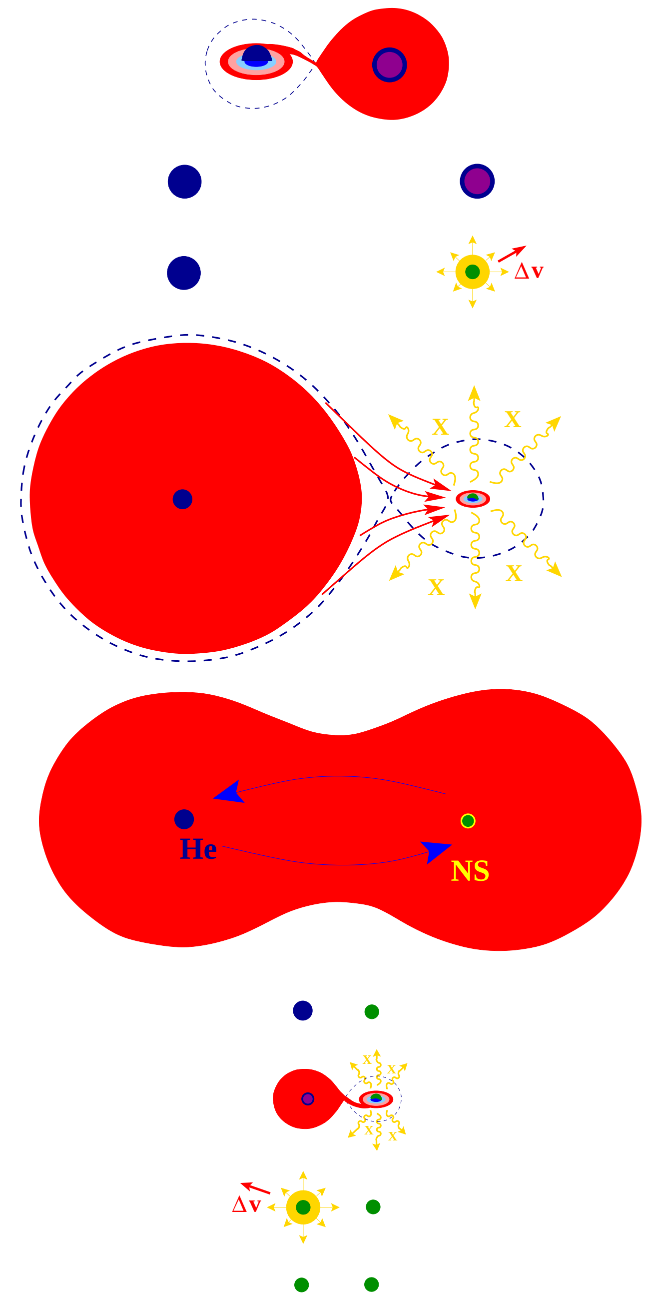
II. Non-dynamical formation

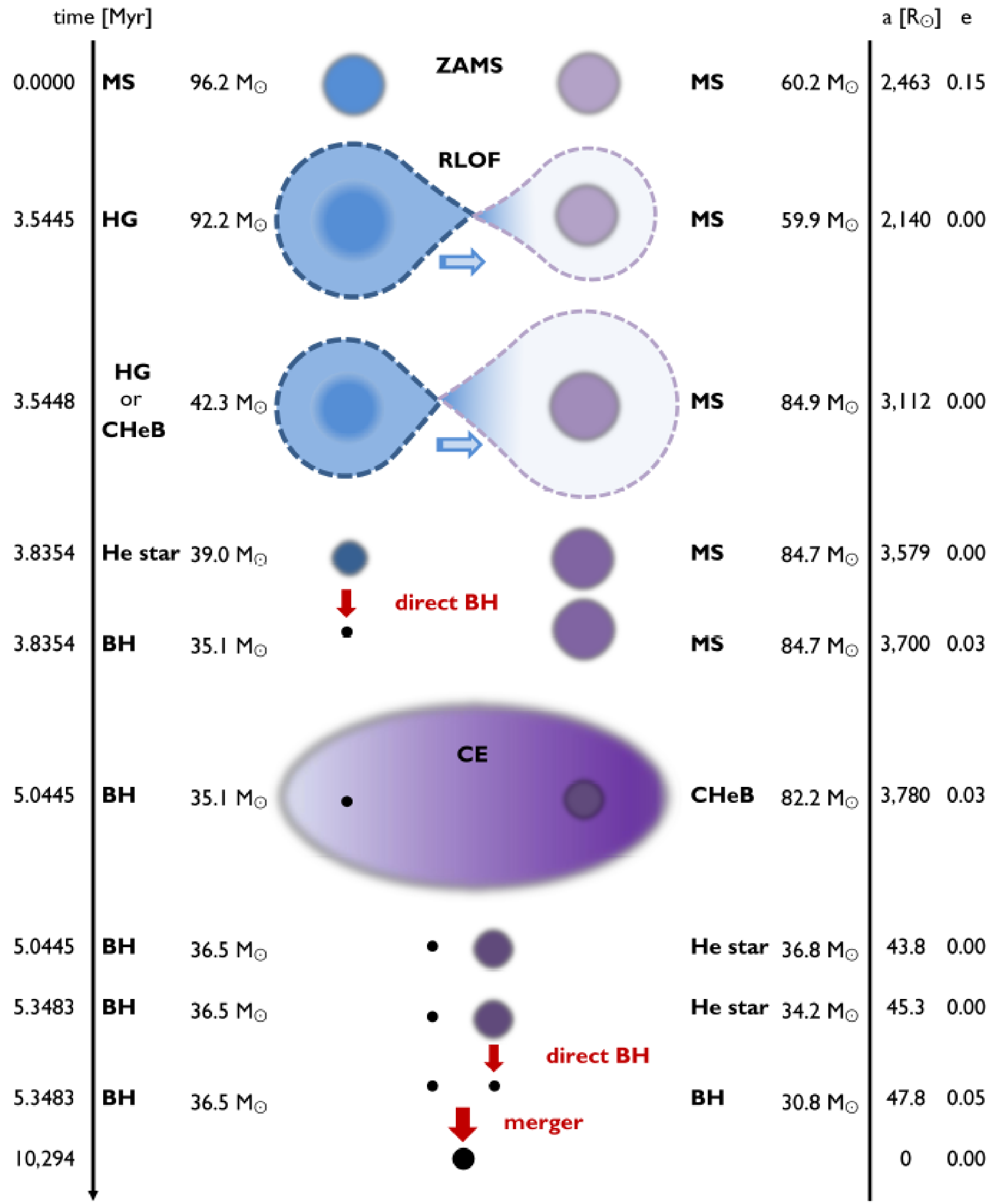
- common-envelope scenarios: conversion of wide binary to close binary
- homogeneous evolution scenarios: close binary from the beginning

Others: primordial BHs, population III stars, core fissioning

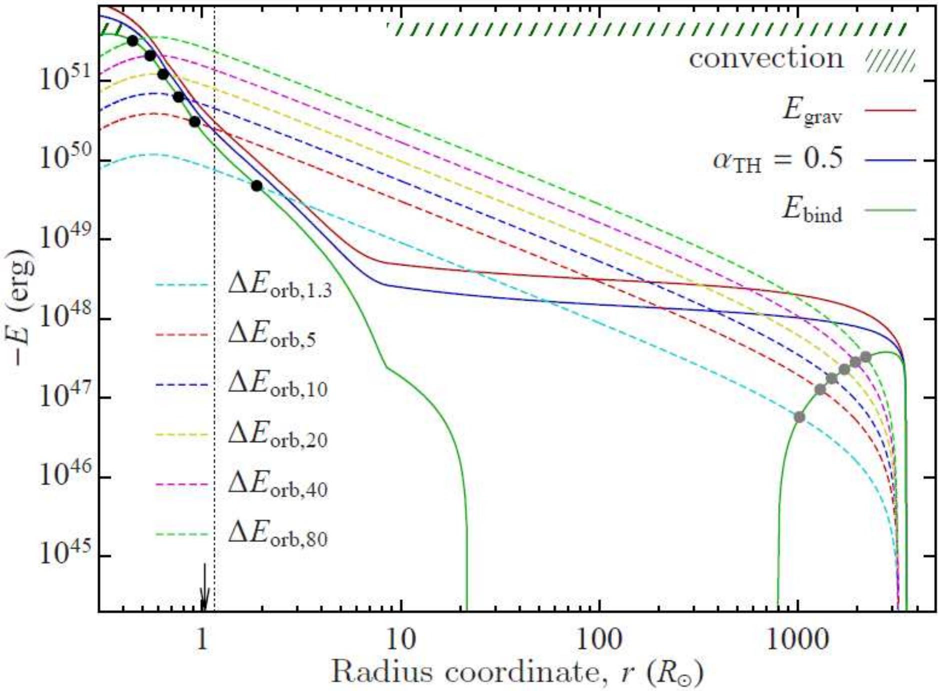
The Formation of BH+BH Binaries through Common-Envelope Evolution

- the progenitors of black holes are big stars
- need to get them into a close orbit to merge
- possible solution: common-envelope evolution
- standard scenario to produce compact NS+NS binaries (Hulse-Taylor pulsar, PSR J0737-3039)
- problem with black holes:
  - ▷ difficult to form two black holes (requires late mass transfer)
  - ▷ but possible with some fine-tuning
  - ▷ rates highly uncertain (Belczynski et al. [2016] vs. Kruckow, et al. [2016])





Belczynski+ (2016)



Kruckow et al. (2016)

- **for massive companions form wide non-merging binaries ($> 50\,R_\odot$)**
- **further spiral-in due to envelope expansion? (not modelled in α formalism)**
- **can form systems like GW150914 with fine-tuning, but rate estimates very uncertain**

Principal Uncertainties

- treatment of CE phase (see Ivanova talk)
- it may be difficult to form the most massive BH binaries (very massive stars do not become red supergiants)

Predictions

- diversity of masses and mass ratios
- spins probably somewhat aligned with the orbit (uncertainties in understanding BH kicks!)

The Massive Overcontact Binary (MOB) Model

(Marchant et al. 2016; also de Mink & Mandel 2016a,b)

- initial homogeneous evolution is enforced by tidal locking in a very close massive binary (de Mink et al. 2009)
- needs to avoid binary widening by stellar wind mass loss

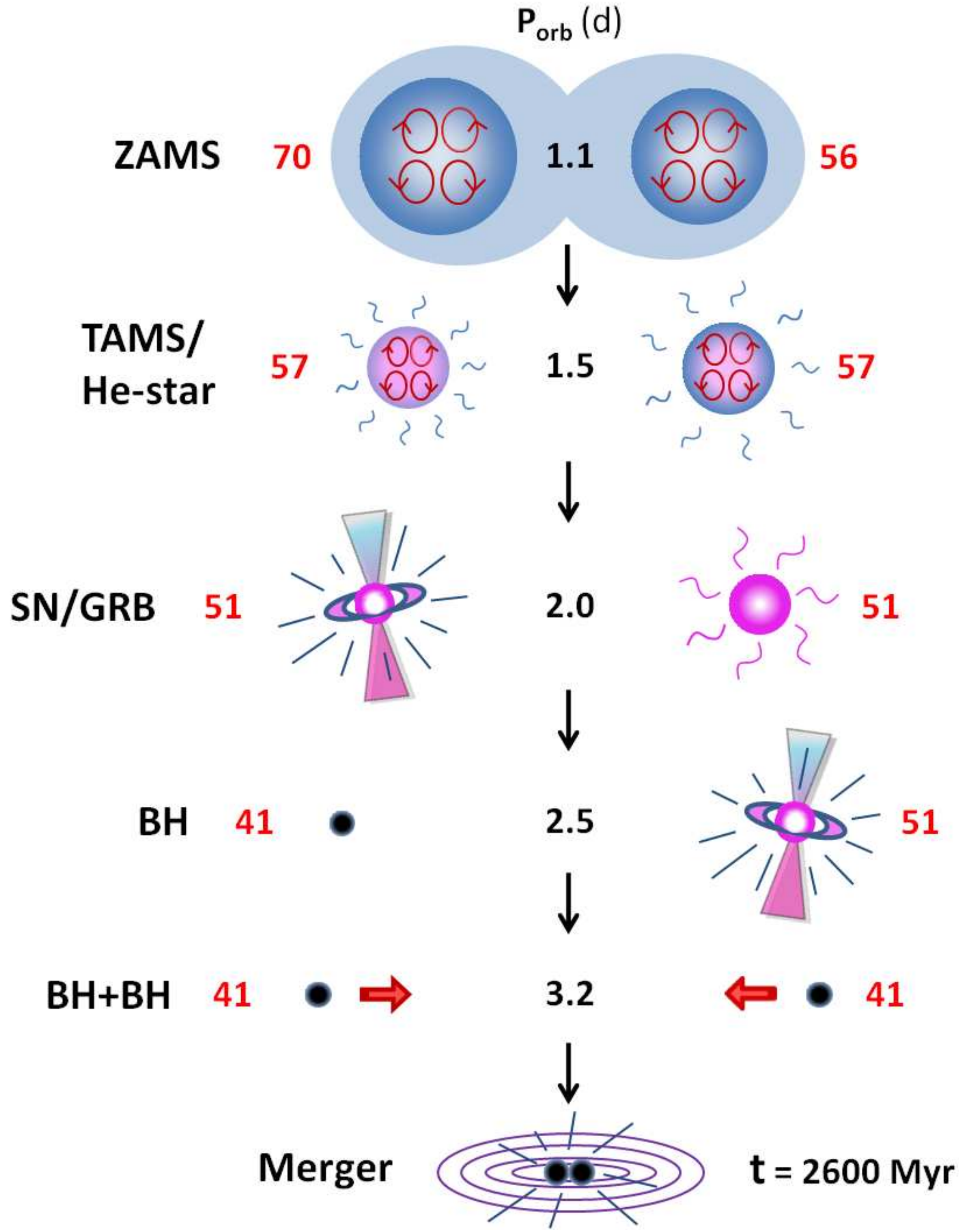
→ requires low metallicity

- most systems pass through contact phase on main sequence

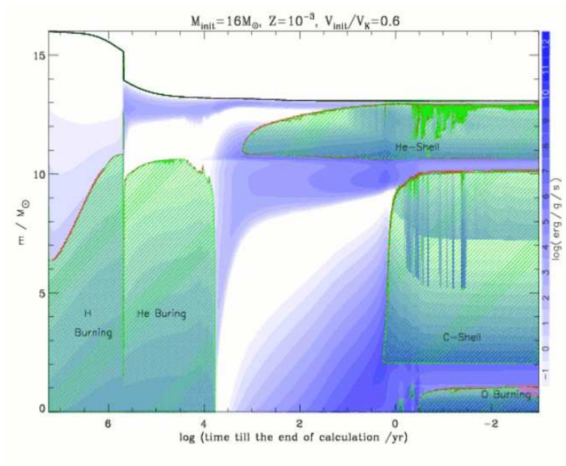
→ evolution drives systems towards mass ratio of 1

Model Description

- uses latest MESA code (Paxton et al. 2015)
- with binary evolution fully implemented (Marchant)
- mass loss:
  - ▷ Vink (2001) $\times 1/3$ (H-rich), Hamann (1995) (no H)
  - ▷ $\dot{M} \propto Z^{0.85}$

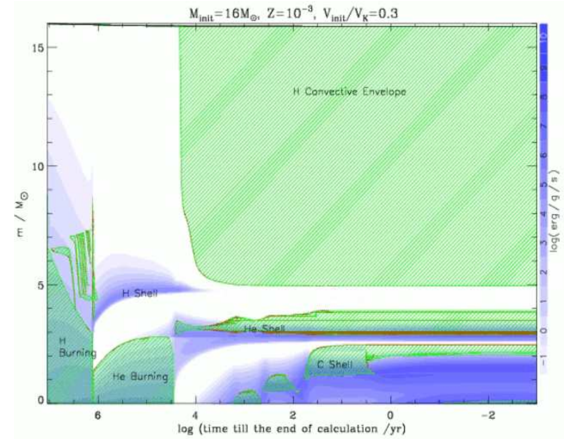


Marchant et al. (2016); after de Mink+ (2009); Mandel/de Mink (2016a,b)

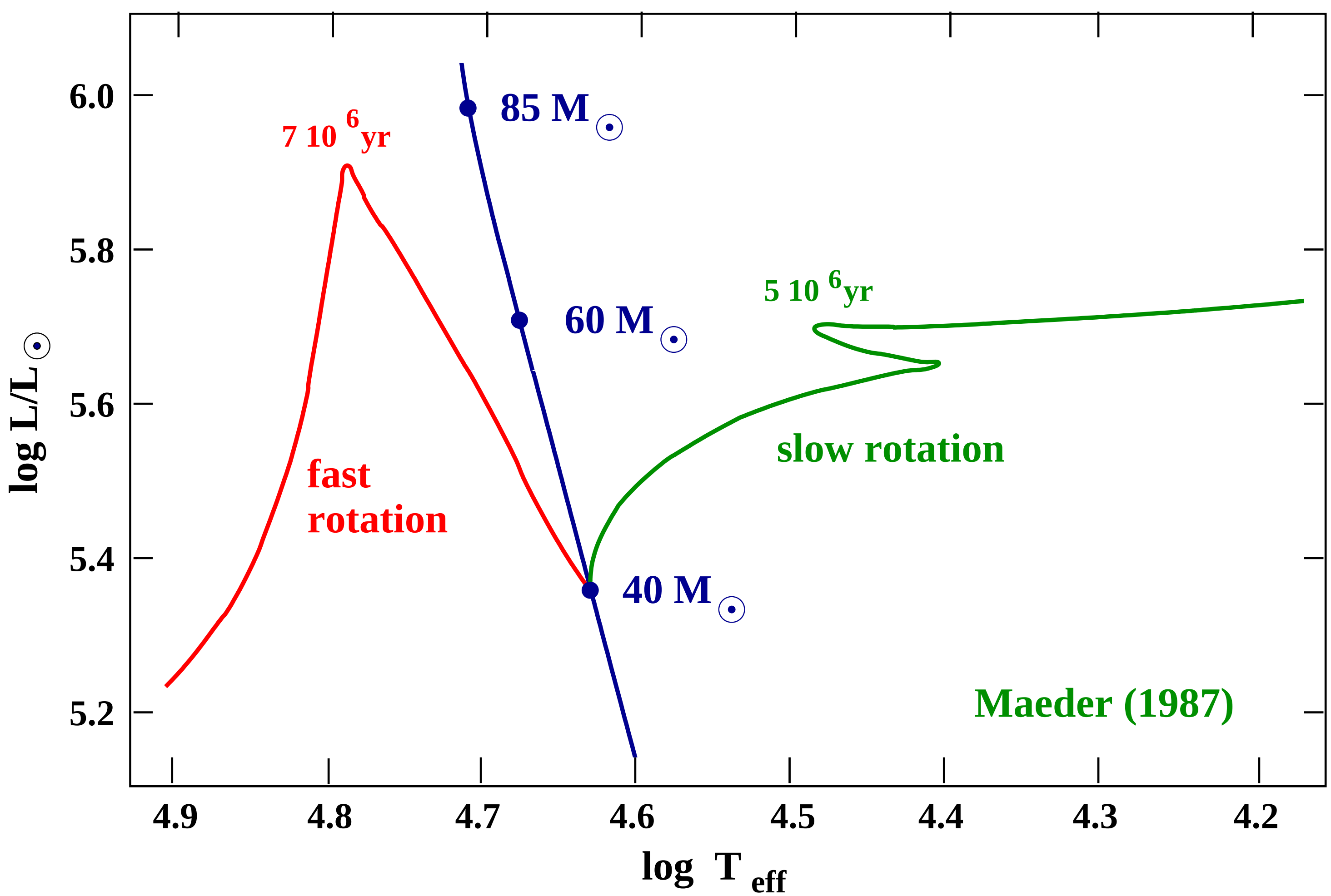


M_init=16M⊙, Z=10^-3, V_init/V_K=0.6
He-Shell
H Burning
He Buring
C-Shell
O Burning
m / M⊙
log(erg / g / s)
log (time till the end of calculation /yr)

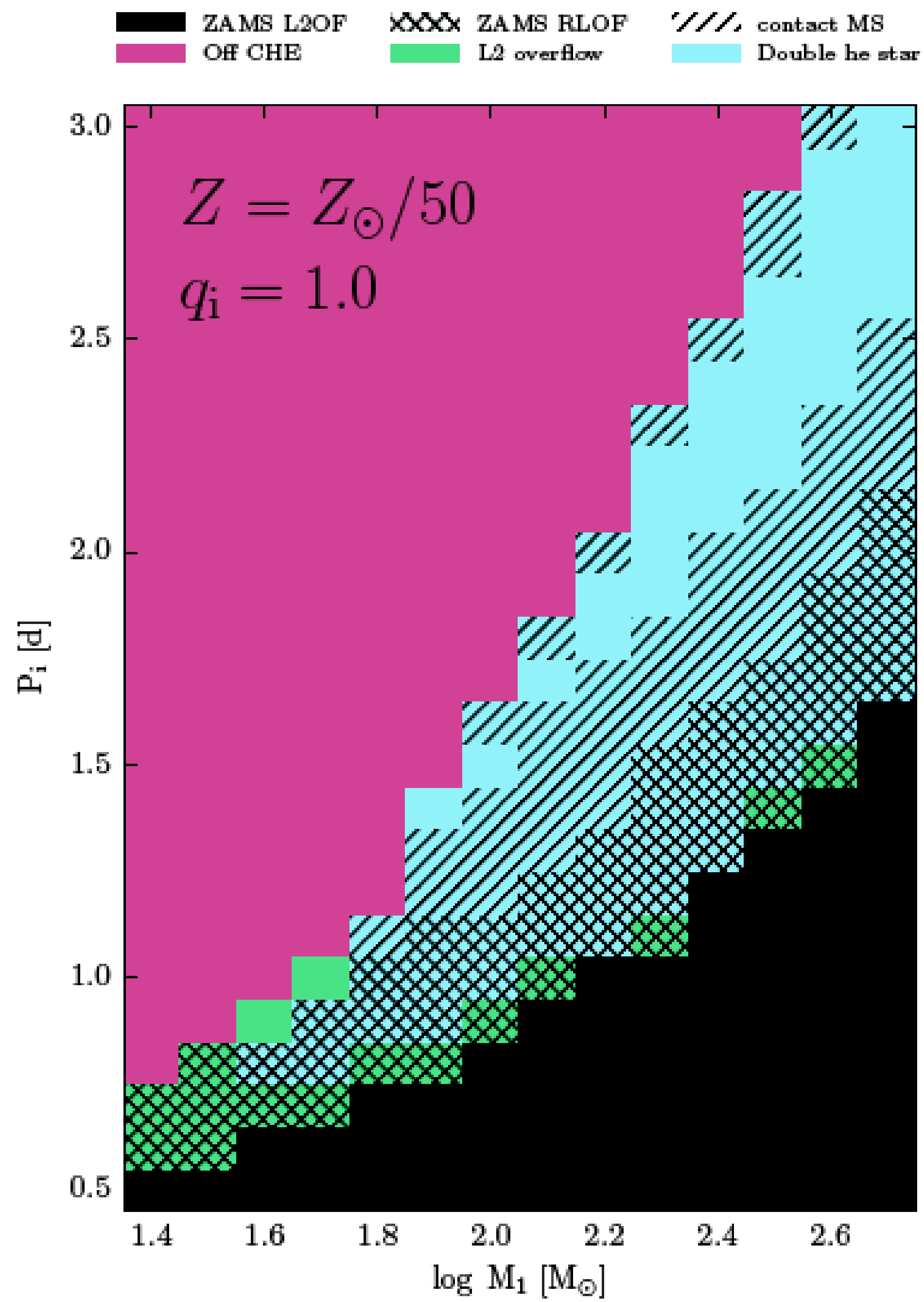
Yoon (2005/6)



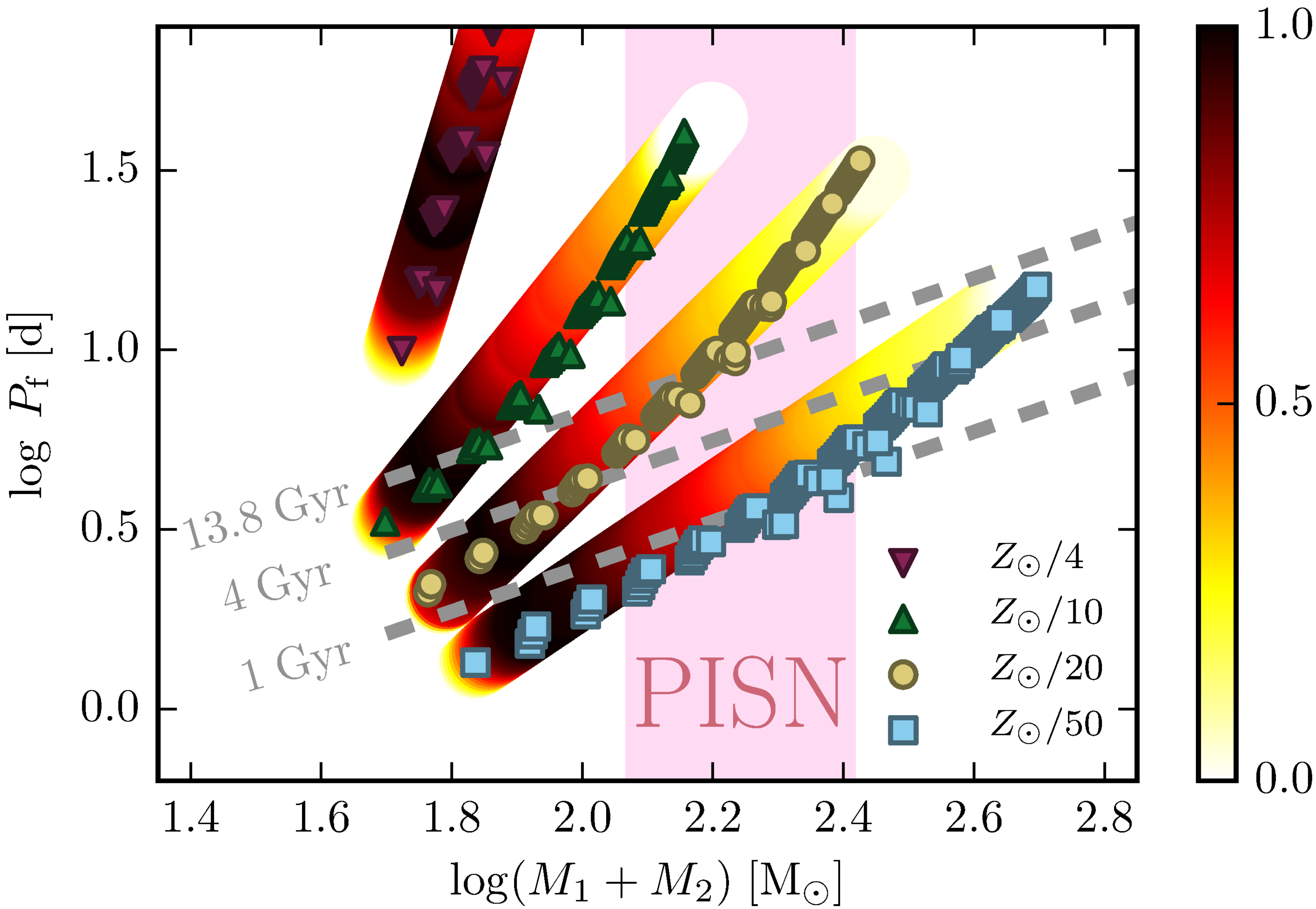
M_init=16M⊙, Z=10^-3, V_init/V_K=0.3
H Convective Envelope
H Shell
He Shell
H Burning
He Burning
C Shell
m / M⊙
log(erg / g / s)
log (time till the end of calculation /yr)



log L/L⊙
log T eff
6.0
5.8
5.6
5.4
5.2
4.9
4.8
4.7
4.6
4.5
4.4
4.3
4.2
7 10 6 yr
85 M⊙
60 M⊙
40 M⊙
5 10 6 yr
slow rotation
fast rotation
Maeder (1987)



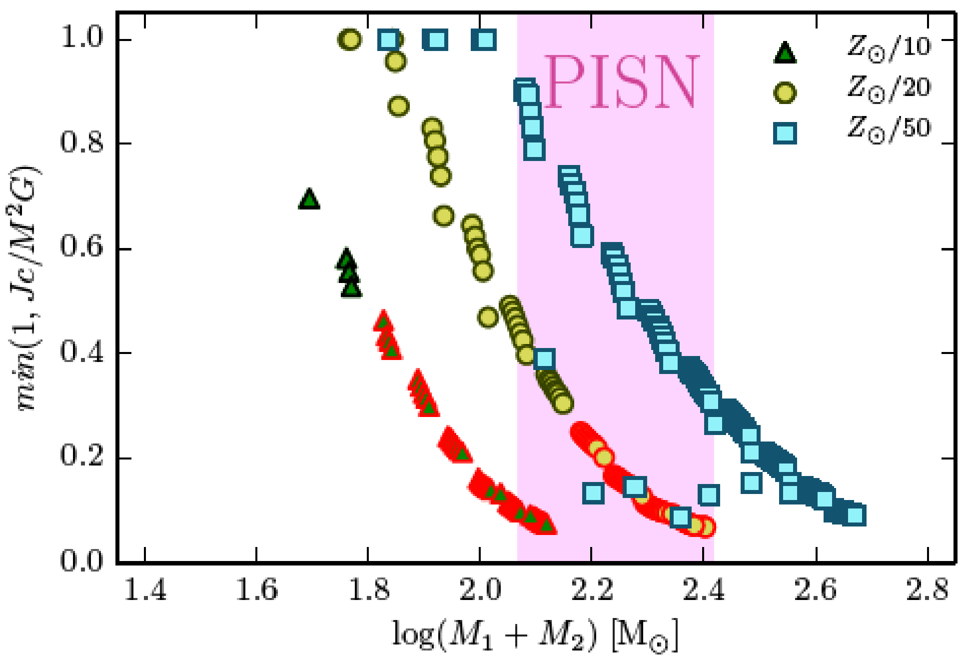
Marchant et al. (2016)



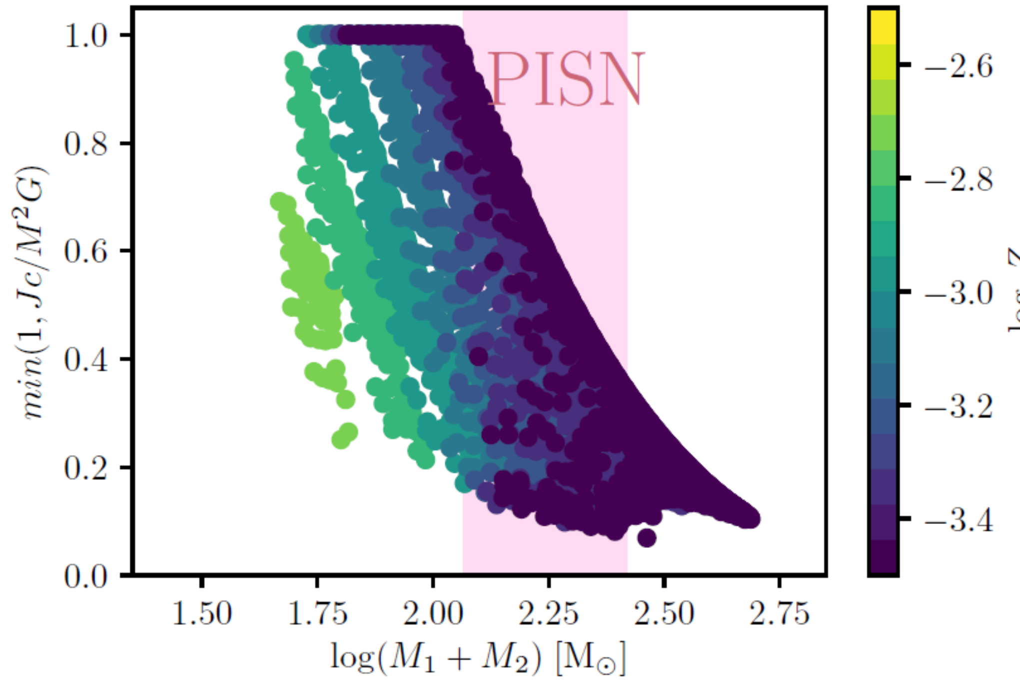
Marchant et al. (2016)

depends on metallicity-dependent stellar winds

Spin Predictions (conservative)



Marchant et al. (2016)

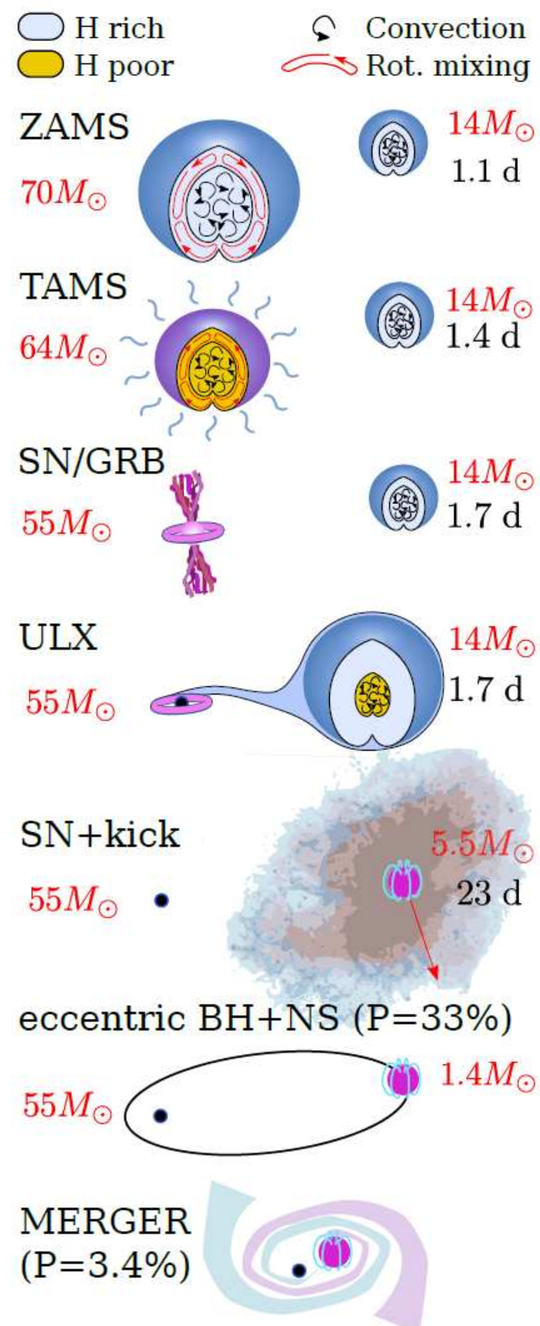


Marchant et al. (2019, preliminary)

Ultraluminous X-ray sources (ULXs) from chemically homogeneous evolution
(Marchant+ 2017)

- ULXs have luminosities $> 10^{39}\,\mathrm{erg/s}$
- probably stellar BH binaries (not intermediate-mass BHs) with super-Eddington radiation (plus beaming?)
- optical counterpart problem: massive optical counterparts require more massive black holes ($\sim 50\,\mathrm{M_\odot}$) (Madhusudhan et al. 2008)
- for mass ratios $\mathrm{q} \simeq 0.1 - 0.4$
  - ▷ massive black holes with massive companion

  rate: up to ~ 2 (per SFR $[\mathrm{M_\odot/yr}]$)
  - ▷ metallicity dependent
  - ▷ lead to the formation of NS+BH binaries

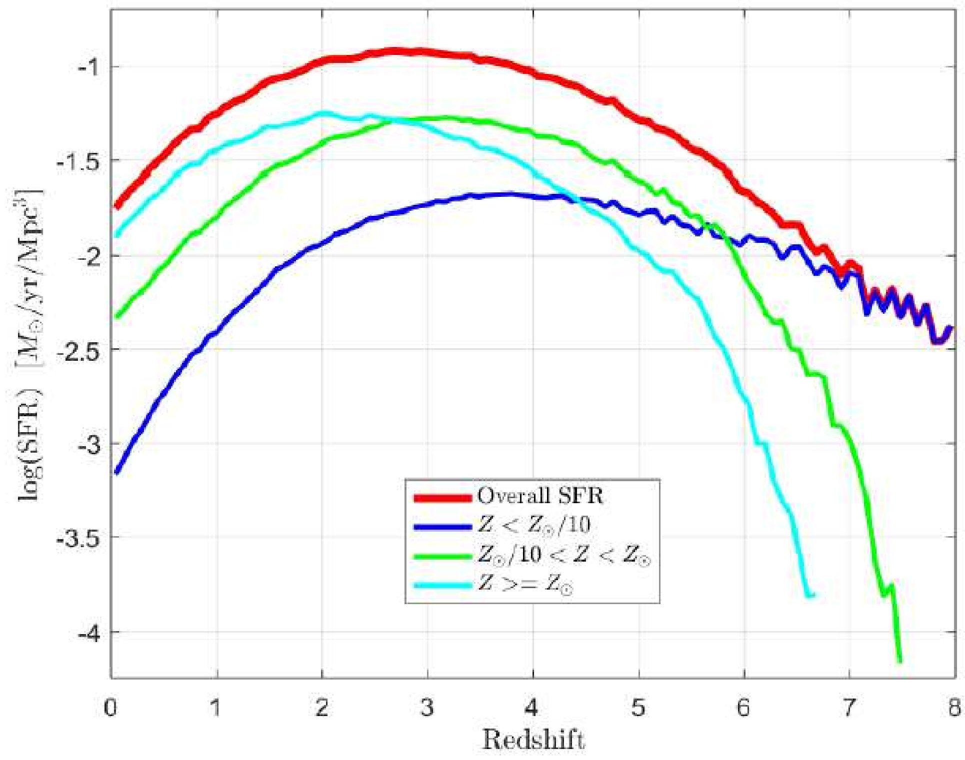


Marchant, Langer, Podsiadlowski+ (2017)

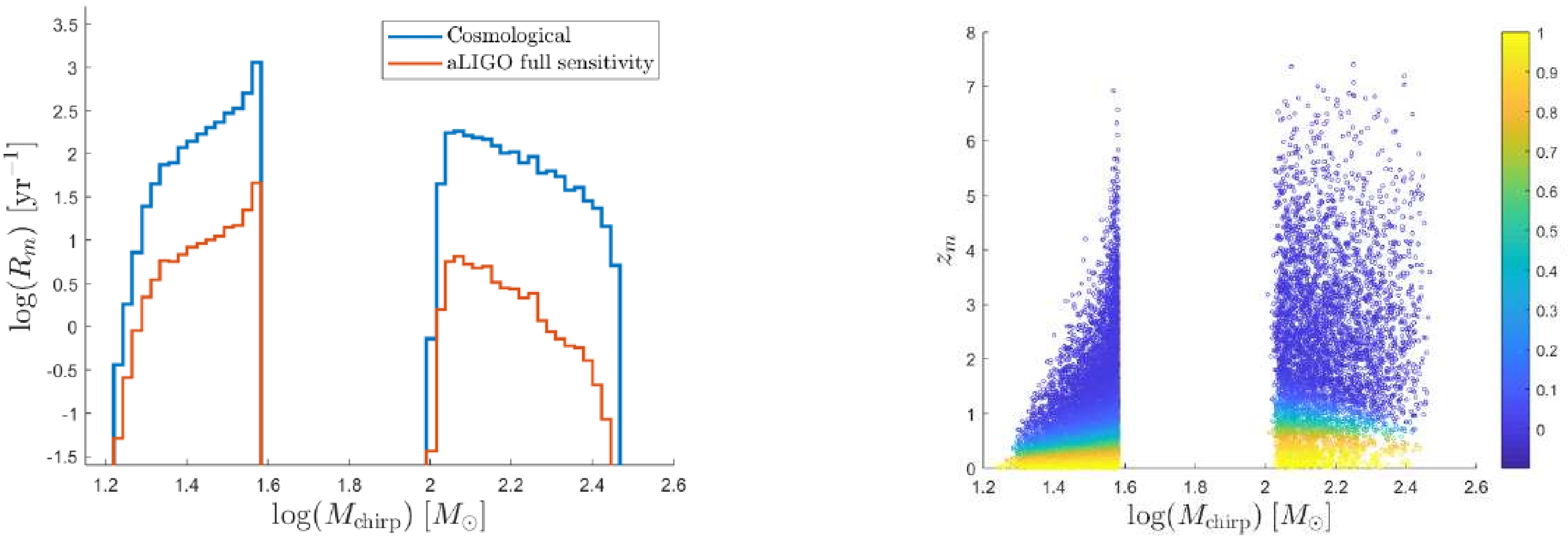
Cosmological Simulations of BH+BH Mergers in the MOB Scenario

Lise du Buisson, Pablo Marchant et al. (2019)

- use full cosmological simulations to simulate rates of GW sources as a function of z and Z (plus LGRBs, PISNe)
- simulations by Taylor & Kobayashi (2014)
  - self-consistent hydrodynamical simulations with star formation, SN and AGN feedback, and chemical enrichment
  - fit key observables, such as the galaxy mass-metallicity relations, metallicity gradients, etc.
- updated binary calculations (PISN gap: $44 - 123\,\mathrm{M}_{\odot}$), Marchant et al. [2018])



Based on Taylor & Kobayashi (2014)



du Buisson et al. (2019)

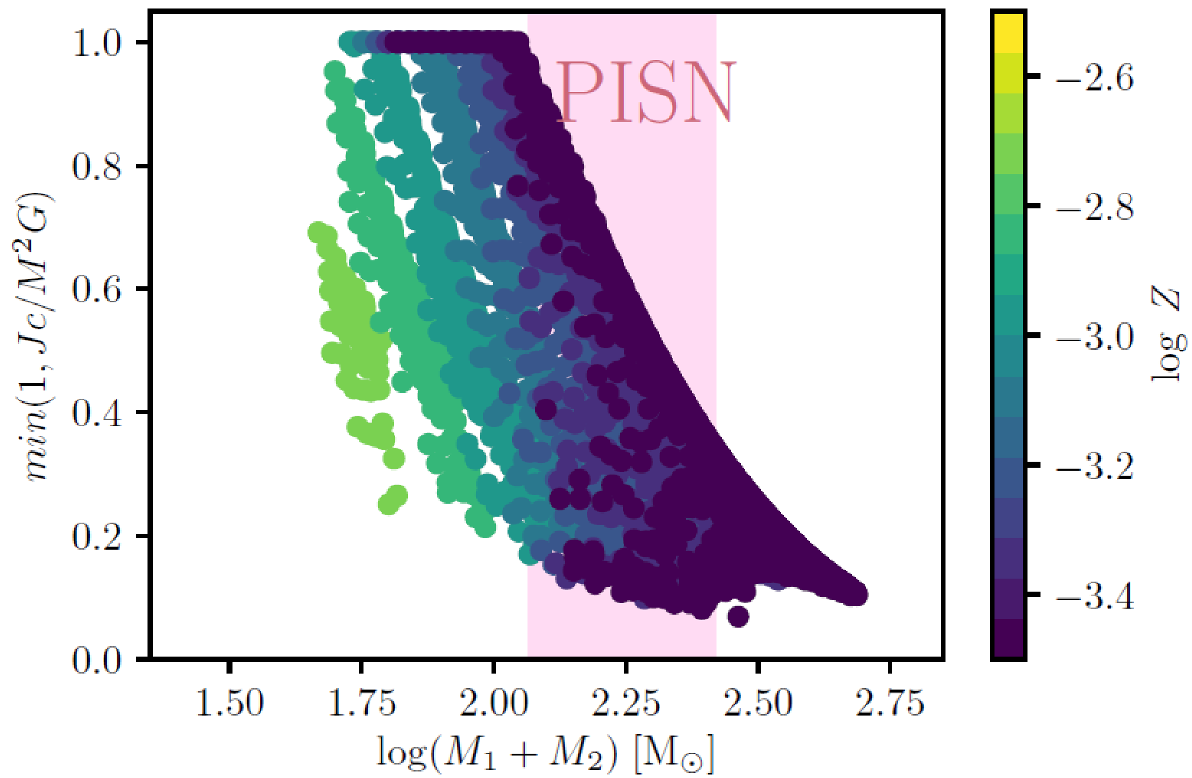
- form massive BH+BH systems ($\gtrsim 25\,\mathrm{M_\odot}$)
- at very low metallicity ($\mathrm{Z_\odot/50}$): bimodal mass distribution with systems below and above pair-instability supernova (PISN) gap (no BH formation)
- prediction for local rate: $\sim 7\,\mathrm{Gpc^{-3}\,yr^{-1}}$, but depends on kick, systems above PISN gap detectable
- known observational counterparts (e.g. double He-star binary (SMC) with $\mathrm{M_1 = 66\,M_1,\ M_2 = 61\,M_2,\ P_{orb} = 19.3\,d}$)

Basic Predictions

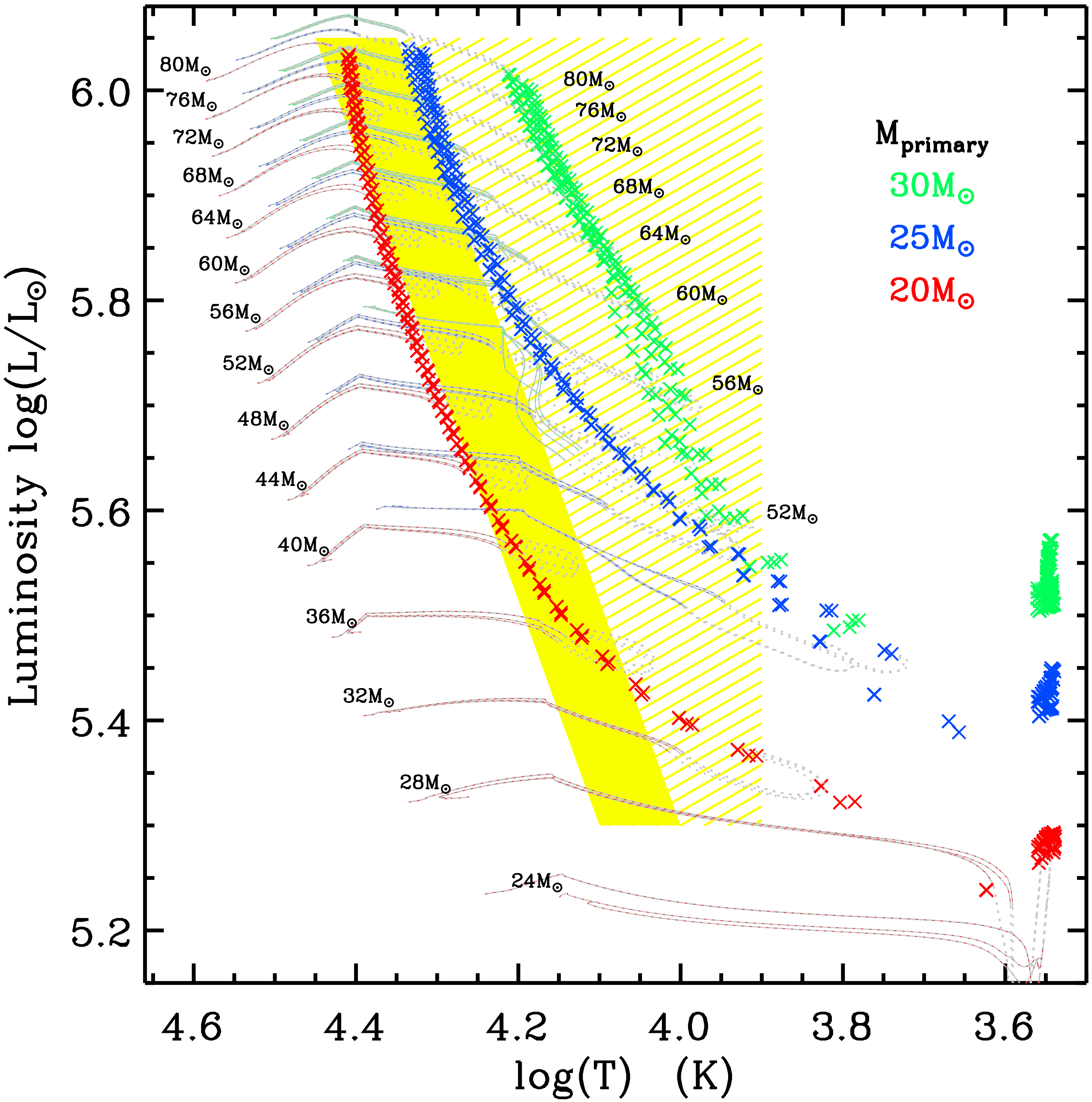
- easier to form massive BH binaries
- 10 % above PISN gap
- mass ratio close to 1 (≥ 0.9?)
- spins vary depending on metallicity, probably correlated with orbit (but depends on BH formation process)

Main Issues

- treatment of rotational mixing untested
- wind mass loss prescription essential (also associated angular momentum loss)



Marchant+ (2019)



Justham et al. (2012)